DTIC FILE COPY

RESEARCH AND DEVELOPMENT TECHNICAL REPORT

SLCET-TR-90-4

AD-A226 028

LITHIUM TETRABORATE TRANSDUCER CUTS

ARTHUR BALLATO, JOHN KOSINSKI, AND THEODORE LUKASZEK

ELECTRONICS TECHNOLOGY AND DEVICES LABORATORY

MARCH 1990

DISTRIBUTION STATEMENT

Approved for public release;
distribution is unlimited.

US ARMY
LABORATORY COMMAND
FORT MONMOUTH, NEW JERSEY 07703-5000

NOTICE

Disclaimer

The citation of trade names and names of manufacturers in this report is not to be construed as official Government indorsement or approval of commercial products or services referenced herein.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) SLCET-TR-90-4	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION US Army Laboratory Command Electronics Tech & Devices Lab	6b. OFFICE SYMBOL (If applicable) SLCET-MA-A
7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State, and ZIP Code) Electronics Technology and Devices Laboratory ATTN: SLCET-MA-A Fort Monmouth, NJ 07703-5000	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
1L162705A	H94	K9	DA303394

11. TITLE (Include Security Classification)

LITHIUM TETRABORATE TRANSDUCER CUTS (U)

12. PERSONAL AUTHOR(S) Arthur Ballato, John Kosinski, and Theodore Lukaszek

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical Report	FROM Dec 88 TO Dec 89	1990 March	22

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
09	01	
17	02	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Piezoelectric resonators; piezoelectric transducers; lithium tetraborate; acousto-optics. (JS)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Lithium tetraborate is a tetragonal material of considerable promise for frequency control and signal processing applications. It exhibits piezoelectric coupling values that fall between those of lithium niobate and quartz, but possesses orientations for which the temperature coefficient of frequency and delay time is zero for bulk and surface acoustic waves.

In this report, we discuss the properties of two doubly rotated bulk wave resonator orientations having both first- and second-order temperature coefficients equal to zero. These are suitable for shear and compressional wave transducers in applications where very low temperature sensitivity is required simultaneously with moderately strong piezocoupling coefficients. Kosinski

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Dr. Arthur Ballato	(201) 544-4308	SLCET-DS

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

CONTENTS

FIGURES

TABLES

INTRODUCTION

Lithium tetraborate (LBO) is a tetragonal material in crystal class 4mm (C_{4v}). As such it possesses a single 4-fold polar axis, and four symmetry planes containing the 4-fold axis. The primitive region is 1/8th of a hemisphere, which we describe in IEEE standard notation as $(yxwl)\Phi/\theta$, with $0 \le \Phi \le \pi/4$ and $0 \le \theta \le \pi/2$. Its 4mm symmetry is indifferent to sign changes in the angles and requires that it be:

- Pyroelectric
- Optically uniaxial (LBO is negative)
- Piezoelectric
- Not enantiomorphic (no twinning)
- Nonferroelectric (poling not required)

There are 6 independent linear elastic constants, three independent linear piezoelectric constants, and two independent linear dielectric constants.

Particularizing to the substance lithium tetraborate (LBO), we find from the literature [1]-[19] the following specific attributes:

Properties of $Li_2B_4O_7 = Li_2O \cdot 2B_2O_3$

- Congruently melting phase in the lithium oxide-boron oxide system; transparent and colorless.
- Melting point: 917°C; low compared to lithium niobate.
- Czochralski growth, Pt crucibles, diameters > 50 mm along [100], [001], or [110]; sensitive to thermal shock.
- Lattice spacings: a = b = 9.479 Å, c = 10.280 Å
- Mohs hardness = 6 (between $LiTaO_3$ and quartz = 7).
- Relatively low density = 2451 kg/m^3, but acoustic velocities are only slightly greater than in $LiNbO_3$ and $LiTaO_3$.
- Solubility: 1) dissolves rapidly in acids, slowly in bases, 2) hot water is used as etchant, 3) insolvent in organic "solvents."
- Relatively high piezocoupling values.
- Surface acoustic wave (SAW) reflectivity per stripe greater than five times that for $LiNbO_3$, $LiTaO_3$, and quartz, leading to miniaturization.
- Zero temperature coefficients of frequency and time delay for BAW and SAW.

TEMPERATURE COMPENSATED PLATE TRANSDUCERS

Thickness vibrations of doubly rotated piezoelectric plates in the one-dimensional approximation are discussed in Ref. [20]. We have applied this formalism to lithium tetraborate, employing the data of Shiosaki, et al. [12], to calculate quantities pertinent to transducer application. Corresponding lithium

niobate (LNO) values have also been computed for the most popular transducer orientations [21], using the data of Smith and Welsh [22], to serve as a basis of comparison.

The calculations for lithium tetraborate disclose the existence of continuous loci of orientations having zero temperature coefficient of plate frequency of either first or second order [09], [18], [19]. These cuts are functions of harmonic of operation, type of mode, and electrical boundary conditions. There exist two orientations for which both the first- and second-order temperature coefficients vanish simultaneously at the fundamental harmonic of the resonance frequency.

Figure 1 gives the loci of first-order, zero temperature coefficients of resonance frequency for the extensional (compressional, thickness-stretch) mode at the fundamental, third, and infinite harmonics as function of the two orientation angles. Figure 2 gives the same plots for the second-order loci.

Figure 3 shows the superposition of the fundamental harmonic loci from Figs. 1 and 2. It is seen that in the vicinity of $\Phi/\theta \approx 40^\circ/33^\circ$ both the linear and parabolic coefficients become zero and the frequency-temperature behavior is at worst cubic, i.e., similar to that of the AT-cut of quartz. This cut (dubbed "TA") is proposed for extensional mode transducer applications when frequency stability with temperature over an extended range is a requirement, jointly with moderate piezoelectric coupling. The reference temperature for all computations is 25°C, but the region of minimum frequency deviation may be adjusted by variation of the phi/theta angles about the intersection point in Fig. 3, as is done with doubly rotated quartz cuts [20].

A second compensated orientation (the "TC" cut) likewise exists for the slow shear mode operating on the fundamental harmonic. The first- and second-order temperature coefficients of frequency both vanish for this cut, whose coordinates are $\Phi/\theta \approx 19^\circ/56^\circ$. The TC cut is proposed for shear mode transducer applications demanding superior frequency stability with temperature, and piezocoupling values larger than available with quartz.

VELOCITY AND PIEZOCOUPLING

The nominal fundamental frequency of a plate resonator on a given mode is one half the appropriate acoustic velocity divided by the thickness. The half-velocity is referred to as the "frequency constant." Figure 4 gives the frequency constants N_m for LBO (yxwl)Φ=45°/θ cuts; index "m" denotes the mode: "a" = extension, "b" = fast shear, and "c" = slow shear. In general, each mode contains an admixture of shear and extension, so an important consideration for transducer application is the purity

of the desired motion. We shall return later to this point when a comparison with lithium niobate is given. The N_m turn out to be quite insensitive to Φ changes in the range $35° \leq \Phi \leq 45°$, so Fig. 4 may be used to infer the theta variation of N_a about the TA cut angle. Values about the TA cut are shown boxed; they bracket the maximum.

The corresponding thickness excitation [TE] piezoelectric coupling factors k_m are plotted in Fig. 5; these are also insensitive to Φ changes in the same range. Shown boxed are the two [TE] coupling factors in an angle range about the TA cut, k_a and k_c; these are nearly of equal strength.

Table 1 lists the frequency constants and piezocoupling coefficients for the three simple thickness modes of TA- and TC-cut lithium tetraborate transducers, as well as for the unrotated Z cut. The k_m are for thickness excitation, [TE], where the driving field is in the direction of the plate thickness, while the $\underline{k}_m$ represent the coupling factors for lateral excitation, [LE], with the field in the plane of the plate [23]. The number in parentheses following $\underline{k}_m$ is the lateral field angle psi in degrees. In IEEE notation the lateral electric field direction can be expressed as a third rotation from the original crystallographic X axis by the symbol (yxwlt)Φ/θ/psi. Also listed in Table 1 are the direction cosines of particle motion, $\beta_m^{(i)}$, for each cut and mode, from which the purity of the mode can be established. The subscript "m" refers to the mode, while the superscript (i) refers to the crystal plate axes; (2) is the plate thickness direction.

TEMPERATURE COEFFICIENTS

Table 2 contains values of the first-order temperature coefficients of lithium tetraborate, with units of 10^{-6}/K, as follows: T_f is the coefficient of the nominal frequency; it is obtained as the difference of the velocity and thickness-directed thermoelastic coefficients. Tk and T$\underline{k}$ are the piezocoupling [TE] and [LE] temperature coefficients. T_{fR} is the coefficient of the [TE] resonance frequency, while T_{fA} is the coefficient of the [LE] antiresonance frequency. T_{fR} is computed from T_f and Tk, and T_{fA} is computed from T_f and T$\underline{k}$; the method is given in Refs. [24] and [25]. In all cases the effects of electrode mass loading are not taken into account. Second-order temperature coefficients have been computed for LBO and are given in Ref. [26].

COMPARISON WITH LITHIUM NIOBATE

Lithium niobate (LNO) has two major transducer orientations: the 36° rotated Y cut (extensional mode), and the unrotated X cut (shear mode). Table 3 lists, for these orientations, and for the

Z cut, the quantities correspondingly given for lithium tetraborate in Table 1. Generally speaking, LNO possesses greater piezocoupling values for both thickness and lateral field excitation. Furthermore, in LNO the shear mode cut is unrotated, and the extensional mode is only singly rotated, making fabrication relatively straightforward; in LBO both transducer cuts are doubly rotated. It appears, then, that niobate enjoys clear advantages over tetraborate as a transducer material when temperature considerations are of no consequence.

When the influence of temperature is important, the situation is reversed. Table 4 provides the first-order temperature coefficients of the nominal plate frequencies for the lithium niobate cuts mentioned above [22], [20]. The values are all quite large. The temperature coefficients of piezoelectric coupling are omitted from this table because they affect the temperature coefficients of the operating frequencies by relatively small amounts, and do not alter the uniform picture of very large, negative temperature coefficients for both thickness and lateral excitation.

By contrast, LBO has both the first- and the second-order temperature coefficients of resonance frequency equal to zero at the TA- and TC-cut orientations, leading to superior performance in thermally sensitive environments.

We now consider the question of the displacements produced by each transducer, i.e., the motional purity. From the last three columns of Tables 1 and 3, one sees that both the TA-cut and the LNO 36° rotated Y cut produce quasi-extensional motion at the "a-mode" resonances, with the shear component of both cuts quite small and of approximately equal magnitude. The extensional transducer cuts are equivalent in respect to this feature. With regard to the shear transducer cuts, the LBO TC-cut "c mode" is quasi-shear in nature, with the extensional component comprising about 28% of the motion. The corresponding LNO X cut has a pure extensional mode, (undriven by [TE]), so the desired "b mode" consists of purely shear motion, albeit at an angle to the in-plane crystallographic axes.

In the tables, the properties of LBO and LNO Z cuts are also compared. This cut has three pure modes, the two shears of which are degenerate. The LBO [TE] "a mode" coupling is greater than that for LNO, but for [LE] the LNO shear coupling exceeds even that of the LNO [TE] X cut "b mode;" this fact has not apparently been generally recognized. The LNO temperature coefficients, however, are very large. For LBO, the temperature situation is much more desirable. The laterally excited shear "c mode," in fact, can have its first-order temperature coefficient of frequency adjusted to be zero by using a "load" capacitor C_L in parallel with the transducer for adjustment, and/or operating at a harmonic other than the fundamental.

CONCLUSIONS

Two doubly rotated lithium tetraborate cuts have been found that possess, for the fundamental harmonic of operation, both first- and second-order zeros of temperature coefficient of frequency, along with moderately strong values of piezoelectric coupling coefficient. One is suitable for extensional mode, and the other for shear mode transducer operation in situations where temperature insensitivity considerations are paramount.

REFERENCES

[01] N. M. Shorrocks, R. W. Whatmore, F. W. Ainger, and I. M. Young, "Lithium Tetraborate: A New Temperature Compensated Piezoelectric Substrate Material for Surface Acoustic Wave Devices," IEEE Ultrasonics Symp. Proc., 1981, pp. 337-340.

[02] B. Lewis, N. M. Shorrocks, and R. W. Whatmore, "An Assessment of Lithium Tetraborate for SAW Applications," IEEE Ultrasonics Symp. Proc., 1982, pp. 389-393.

[03] Y. Ebata, H. Suzuki, S. Matsumura, and K. Fukuta, "SAW Propagation Characteristics on $Li_2B_4O_7$," Proc. 3rd Symp. Ultrasonic Elx., Tokyo, 1982; Jpn. J. Appl. Phys., Vol. 22, 1983, Suppl. 22-3, pp. 160-162.

[04] C. D. J. Emin and J. F. Werner, "The Bulk Acoustic Wave Properties of Lithium Tetraborate," Proc. 37th Annual Frequency Control Symp., June 1983, pp. 136-143.

[05] R. C. Peach, C. D. J. Emin, J. F. Werner, and S. P. Doherty, "High Coupling Piezoelectric Resonators Using Lithium Tetraborate," IEEE Ultrasonics Symp. Proc., 1983, pp. 521-526.

[06] K. Fukuta, J. Ushizawa, H. Suzuki, Y. Ebata, and S. Matsumura, "Growth and Properties of $Li_2B_4O_7$ Single Crystal for SAW Device Applications," Proc. 4th Meeting on Ferroelectric Materials and Their Applications, Kyoto, 1983; Jpn. J. Appl. Phys., Vol. 22, 1983, Suppl. 22-2, pp. 140-142.

[07] T. Shiosaki, M. Adachi, H. Kobayashi, K. Araki, and A. Kawabata, "Elastic, Piezoelectric, Acousto-Optic and Electro-Optic Properties of $Li_2B_4O_7$," Proc. 5th Symp. Ultrasonic Elx., Tokyo, 1984, pp. 5-8; Jpn. J. Appl. Phys., Vol. 24, 1985, Suppl. 24-1, pp. 25-27.

[08] M. Adachi, T. Shiosaki, and A. Kawabata, "Crystal Growth of Lithium Tetraborate ($Li_2B_4O_7$)," Proc. 5th Meeting on Ferroelectric Materials and Their Applications, Kyoto, 1985; Jpn. J. Appl. Phys., Vol. 24, 1985, Suppl. 24-3, pp. 72-75.

[09] Y. Fujiwara, M. Ono, M. Sakai, and N. Wakatsuki, "Strip

Type Resonator of Lithium Tetraborate," Proc. 39th Annual Frequency Control Symp., May 1985, pp. 351-355.

[10] M. Adachi, T. Shiosaki, H. Kobayashi, O. Ohnishi, and A. Kawabata, "Temperature Compensated Piezoelectric Lithium Tetraborate Crystal for High Frequency Surface Acoustic Wave and Bulk Wave Device Applications," IEEE Ultrasonics Symp. Proc , 1985, pp. 228-232.

[11] A. S. Bhalla, L. E. Cross, and R. W. Whatmore, "Pyroelectric and Piezoelectric Properties of Lithium Tetraborate Single Crystal," Jpn. J. Appl. Phys., Vol. 24, 1985, Suppl. 24-2, pp. 727-729.

[12] T. Shiosaki, M. Adachi, and A. Kawabata, "Growth and Properties of Piezoelectric Lithium Tetraborate Crystal for BAW and SAW Devices," IEEE Intl. Symp. Applications Ferroelectrics (ISAF) Proc., Lehigh University, Bethlehem, PA, June 1986, pp. 455-464.

[13] Y. Ebata and M. Koshino, "SAW Resonator and Resonator Filter on $Li_2B_4O_7$ Substrate," Jpn. J. Appl. Phys., Vol. 26, 1987, Suppl. 26-1, pp. 123-125.

[14] H. Abe, H. Saitou, M. Ohmura, T. Yamada, and K. Miwa, "Lithium Tetraborate ($Li_2B_4O_7$) SAW Resonators," IEEE Ultrasonics Symp. Proc. 1987, pp. 91-94.

[15] W. S. Ishak, C. A. Flory, and B. A. Auld, "Acoustic Modes in Lithium Tetraborate," *IEEE Ultrasonics* Symp. Proc., 1987, pp. 241-245.

[16] S. Matsumura, T. Omi, N. Yamaji, and Y. Ebata, "A 45^o X Cut $Li_2B_4O_7$ Single Crystal Substrate for SAW Resonators," IEEE Ultrasonics Symp. Proc., 1987, pp. 247-250.

[17] M. Murota and Y. Shimizu, "Characteristics of Leaky Surface Waves Propagating on $Li_2B_4O_7$," IEEE Ultrasonics Symposium Proc., Montréal, Canada, October 1989, pp. 291-294.

[18] A. Ballato, J. Kosinski, M. Mizan, and T. Lukaszek, "Lateral- and Thickness-Field Coupling in Lithium Tetraborate," Proc. 43rd Annual Frequency Control Symp., May-June 1989, pp. 557-562.

[19] A. Ballato, J. Kosinski, and T. Lukaszek, "Lateral-Field Temperature Behavior of Lithium Tetraborate," IEEE Ultrasonics Symp. Proc., Montréal, Canada, October 1989, pp. 441-444.

[20] A. Ballato, "Doubly Rotated Thickness Mode Plate Vibrators," in Physical Acoustics: Principles and Methods, (W. P. Mason and R. N. Thurston, eds.) Vol. 13, Chap. 5, pp. 115-181. Academic, New York, 1977.

[21] A. Ballato, "Electromechanical Coupling Factors of Lithium Niobate," in Properties of Lithium Niobate, INSPEC/EMIS Datareview Series No. 5, pp. 122-126. IEE, London, 1989.

[22] R. T. Smith and F. S. Welsh, "Temperature Dependence of the Elastic, Piezoelectric, and Dielectric Constants of Lithium Tantalate and Lithium Niobate," J. Appl. Phys., Vol. 42, No. 6, May 1971, pp. 2219-2230.

[23] T. Yamada and N. Niizeki, "Admittance of Piezoelectric Plates Vibrating under the Perpendicular Field Excitation," Proc. IEEE, Vol.58, No.6, June 1970, pp. 941-942; "Formulation of Admittance for Parallel Field Excitation of Piezoelectric Plates," J. Appl. Phys., Vol. 41, No. 9, August 1970, pp. 3604-3609; "A New Formulation of Piezoelectric Plate Thickness Vibration," Rev. Elec. Comm. Lab. NTT (Tokyo), Vol. 19, Nos. 5-6, May-June 1971, pp. 705-713.

[24] M. Onoe, "Relationship between Temperature Behavior of Resonant and Antiresonant Frequencies and Electromechanical Coupling Factors of Piezoelectric Resonators," Proc. IEEE, Vol. 57, No. 4, April 1969, pp. 702-703.

[25] A. Ballato, "Apparent Orientation Shifts of Mass-Loaded Plate Vibrators," Proc. IEEE, Vol. 64, No. 9, September 1976, pp. 1449-1450.

[26] A. Ballato, J. Kosinski, M. Mizan, and T. Lukaszek, "Temperature and Coupling Behavior of Resonators and Transducers of Lithium Tetraborate Driven by Lateral- and Thickness Fields, Technical Report SLCET-TR-90-1, US Army Laboratory Command, Fort Monmouth, NJ, January 1990, 88pp.

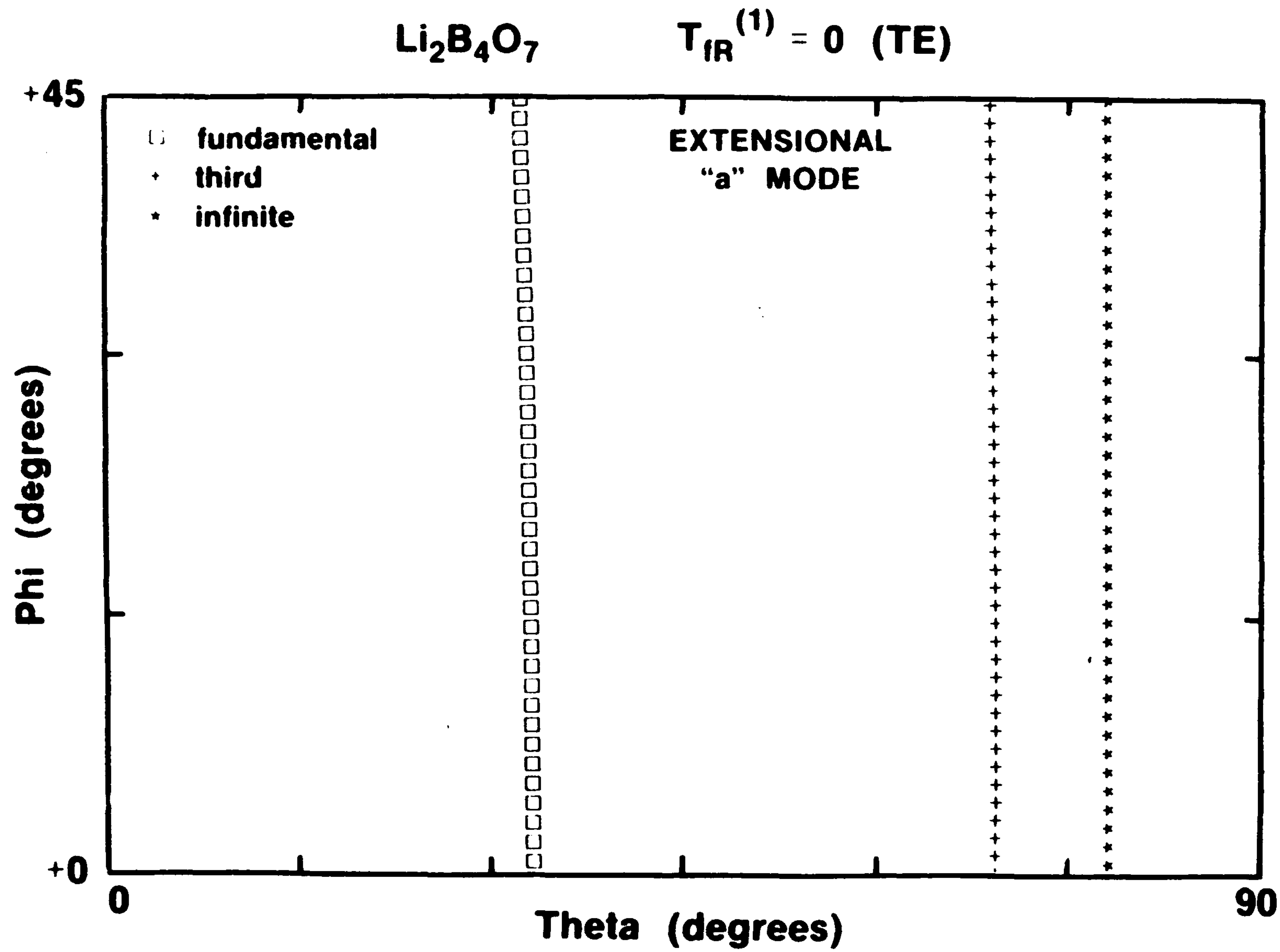

Figure 1. Loci of zeros of first-order temperature coefficients of thickness-stretch frequencies of $(yxwl)\Phi/\Theta$ plate transducers operating at the fundamental, third, and infinite harmonics.

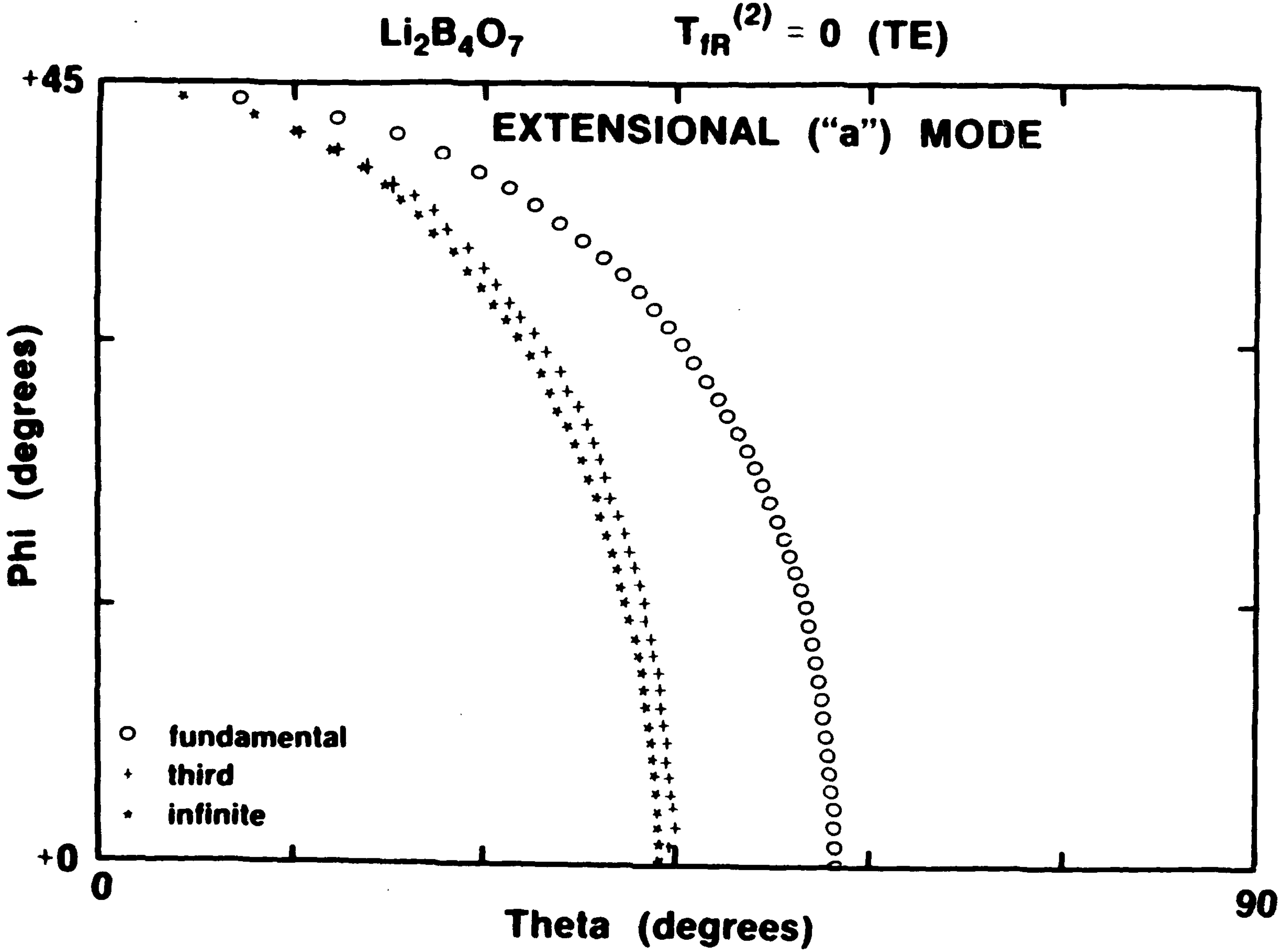

Figure 2. Loci of zeros of second-order temperature coefficients of thickness-stretch frequencies of (yxwl)Φ/Θ plate transducers operating at the fundamental, third, and infinite harmonics.

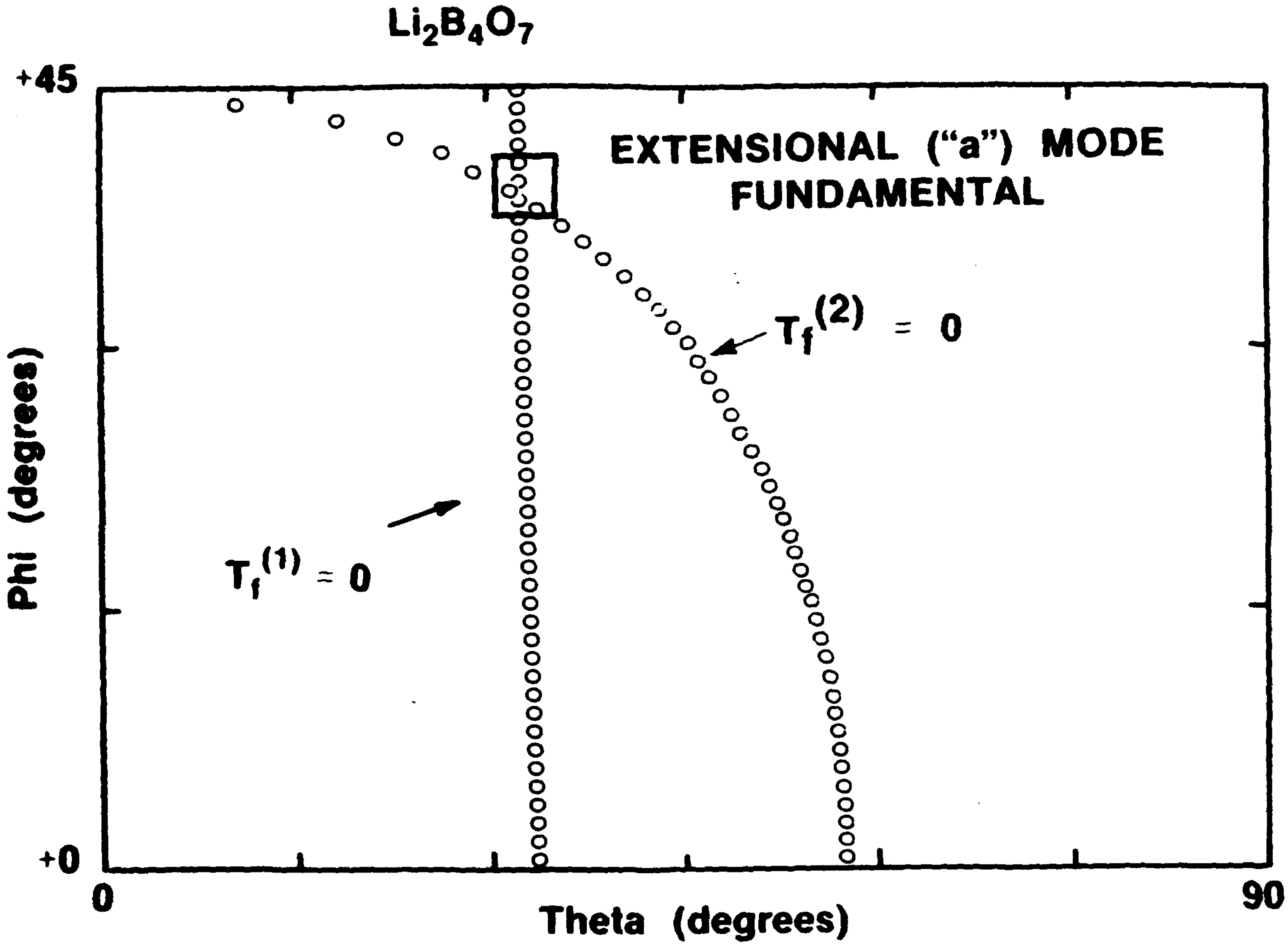

Figure 3. Loci of zeros of first- and second-order temperature coefficients of thickness-stretch frequencies of (yxwl)Φ/Θ plate transducers operating at the fundamental harmonic.

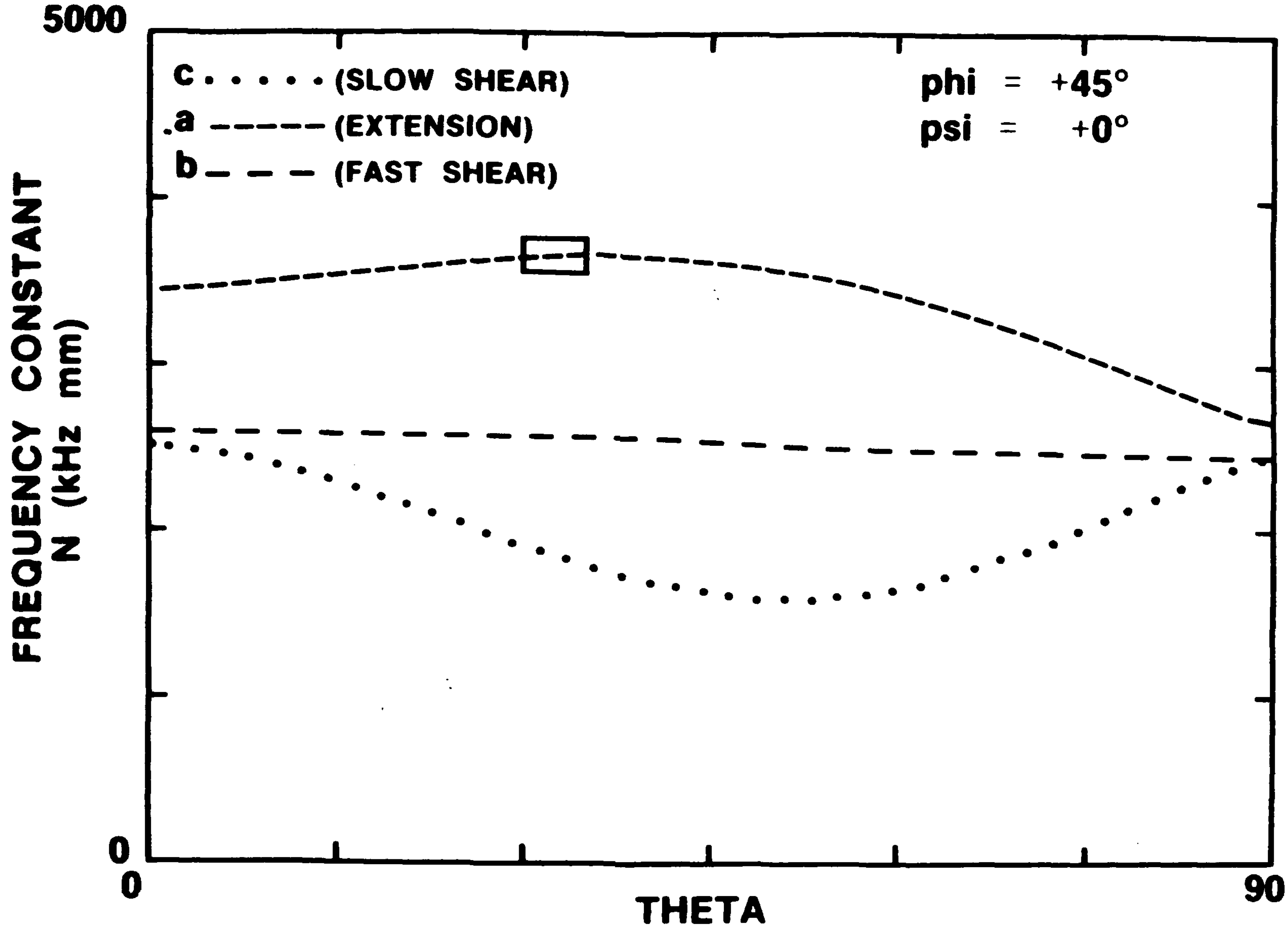

Figure 4. Frequency constants for (yxwl)Φ = 45°/θ open-circuited plate transducers driven by thickness-directed fields.

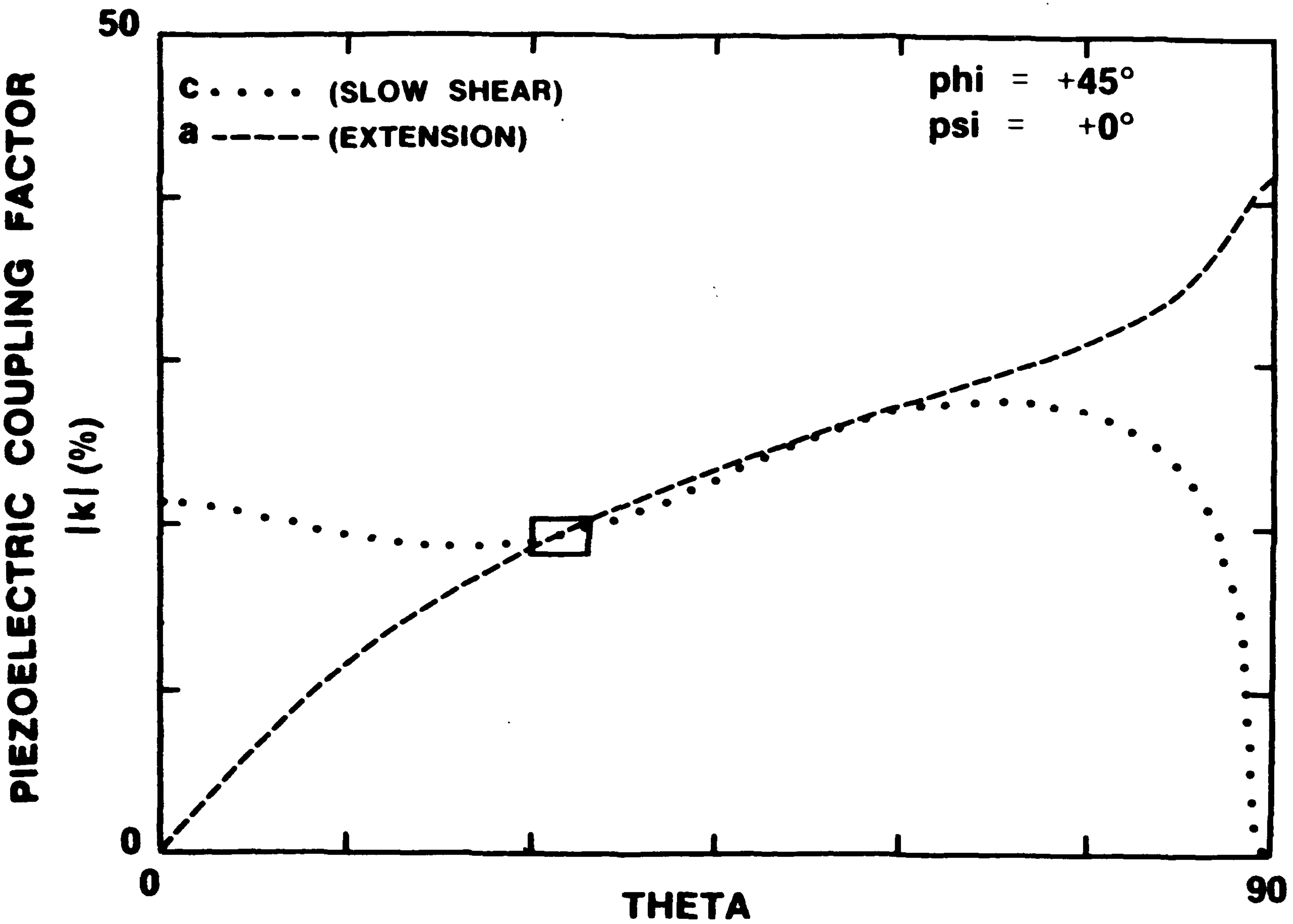

Figure 5. Thickness excitation piezocoupling factors for (yxwl)ϕ = 45°/θ plate transducers.

TABLE 1. PROPERTIES OF LITHIUM TETRABORATE ZERO TEMPERATURE COEFFICIENT TRANSDUCER CUTS.

LBO CUT	ANGLE		MODE	N_m (MHz-mm)	k_m (%)	$\underline{k}_m(0)$ (%)	$\underline{k}_m(90)$ (%)	$\beta_m(1)$	$\beta_m(2)$	$\beta_m(3)$
	ϕ°	θ°								
TA	40	33	a *	3.66	19.7	0.2	6.3	+2.86E-2	+9.99E-1	+6.82E-3
			b	2.55	1.4	11.5	0.6	-9.99E-1	+2.83E-2	+4.24E-2
			c	1.84	19.7	0.7	9.7	+4.22E-2	-8.02E-3	+9.99E-1
TC	19	56	a	3.52	26.0	0.4	0.2	+3.49E-2	+9.61E-1	-2.76E-1
			b	2.42	2.4	18.4	1.0	-9.98E-1	+5.05E-2	+4.95E-2
			c *	1.65	26.6	1.7	23.1	+6.15E-2	+2.73E-1	+9.60E-1
Z	0	90	a	2.66	41.9	0.	0.	0.	1.	0.
			b	2.45	0.	0.	0.	0.	0.	1.
			c	2.45	0.	22.0	22.0	1.	0.	0.

*Fundamental harmonic.

TABLE 2. TEMPERATURE COEFFICIENTS OF LITHIUM TETRABORATE TRANSDUCER CUTS ($\times 10^{-6}$/K).

LBO CUT	ANGLE		MODE	T_f	Tk_m	$T\underline{k}_m(0)$	$T\underline{k}_m(90)$	T_{fR}	$T_{fA}(0)$	$T_{fA}(90)$
	$\phi°$	$\theta°$								
TA	40	33	a *	- 31.	-970.	- 782.	- 957.	0.	- 31.	- 34.
			b	- 59.	-614.	-1,078.	- 616.	- 59.	- 71.	- 59.
			c	-110.	-966.	- 622.	- 983.	- 78.	-110.	-117.
TC	19	56	a	- 19.	-972.	- 935.	- 799.	+ 39.	- 19.	- 19.
			b	- 29.	-718.	-1,102.	- 842.	- 29.	- 58.	- 29.
			c *	- 55.	-834.	- 859.	-1,033.	0.	- 55.	- 97.
Z	0	90	a	- 9.	-925.	0.	0.	+157.	- 9.	- 9.
			b	+ 7.	0.	0.	0.	+ 7.	+ 7.	+ 7.
			c	+ 7.	0.	-1,132.	-1,132.	+ 7.	- 35.	- 35.

*Fundamental harmonic.

TABLE 3. PROPERTIES OF LITHIUM NIOBATE TRANSDUCER CUTS.

LNO CUT	ANGLE		MODE	N_m (MHz-mm)	k_m (%)	$\underline{k}_m(0)$ (%)	$\underline{k}_m(90)$ (%)	$\beta_m(1)$	$\beta_m(2)$	$\beta_m(3)$
	$\phi°$	$\theta°$								
36° rot.	0	36	a *	3.70	48.7	0.	18.9	0.	+9.98E-1	+6.31E-2
			b	2.03	0.	4.8	0.	+1.	0	0.
			c	2.00	0.	0.	13.1	0.	+6.31E-2	-9.98E-1
X	90	0	a	3.31	0.	27.2	3.2	0.	+1.	0.
			b *	2.40	68.9	0.	0.	-6.12E-1	0.	+7.91E-1
			c	2.03	7.0	0.	0.	+7.91E-1	0.	+6.12E-1
Z	0	90	a	3.67	16.9	0.	0.	0.	1.	0.
			b	1.79	0.	0.	0.	0.	0.	1.
			c	1.79	0.	77.9	77.9	1.	0.	0.

*Fundamental harmonic.

TABLE 4. TEMPERATURE COEFFICIENTS OF LITHIUM NIOBATE TRANSDUCER CUTS.

LNO CUT	ANGLE		MODE	T_f (10^{-6}/K)
	Φ°	θ°		
36° rot.	0	36	a *	-65.
			b	-77.
			c	-78.
X	90	0	a	-83.
			b *	-59.
			c	-79.
Z	0	90	a	-43.
			b	-91.
			c	-91.

*Fundamental harmonic.

ELECTRONICS TECHNOLOGY AND DEVICES LABORATORY
MANDATORY DISTRIBUTION LIST
CONTRACT OR IN-HOUSE TECHNICAL REPORTS

Defense Technical Information Center*
ATTN: DTIC-FDAC
Cameron Station (Bldg 5)
Alexandria, VA 22304-6145

(*Note: Two copies for DTIC will be sent from STINFO Office.)

Director
US Army Material Systems Analysis Actv
ATTN: DRXSY-MP
001 Aberdeen Proving Ground, MD 21005

Commander, AMC
ATTN: AMCDE-SC
5001 Eisenhower Ave.
001 Alexandria, VA 22333-0001

Commander, LABCOM
ATTN: AMSLC-CG, CD, CS (In turn)
2800 Powder Mill Road
001 Adelphi, Md 20783-1145

Commander, LABCOM
ATTN: AMSLC-CT
2800 Powder Mill Road
001 Adelphi, MD 20783-1145

Commander,
US Army Laboratory Command
Fort Monmouth, NJ 07703-5000
1 - SLCET-DD
2 - SLCET-DT (M. Howard)
1 - SLCET-DB
35 - Originating Office

Commander, CECOM
R&D Technical Library
Fort Monmouth, NJ 07703-5000
1 - ASQNC-ELC-I-T (Tech Library)
3 - ASQNC-ELC-I-T (STINFO)

Advisory Group on Electron Devices
201 Varick Street, 9th Floor
002 New York, NY 10014-4877

ELECTRONICS TECHNOLOGY AND DEVICES LABORATORY
SUPPLEMENTAL CONTRACT DISTRIBUTION LIST
(ELECTIVE)

Director
Naval Research Laboratory
ATTN: CODE 2627
001 Washington, DC 20375-5000

Cdr, PM JTFUSION
ATTN: JTF
1500 Planning Research Drive
001 McLean, VA 22102

Rome Air Development Center
ATTN: Documents Library (TILD)
001 Griffiss AFB, NY 13441

Deputy for Science & Technology
Office, Asst Sec Army (R&D)
001 Washington, DC 20310

HQDA (DAMA-ARZ-D/Dr. F.D. Verderame)
001 Washington, DC 20310

Dir, Electronic Warfare/Reconnaissance
Surveillance and Target Acquisition Ctr
ATTN: AMSEL-EW-D
001 Fort Monmouth, NJ 07703-5000

Dir, Reconnaissance Surveillance and
Target Acquisition Systems Directorate
ATTN: AMSEL-EW-DR
001 Fort Monmouth, NJ 07703-5000

Cdr, Marine Corps Liaison Office
ATTN: AMSEL-LN-MC
001 Fort Monmouth, NJ 07703-5000

Dir, US Army Signals Warfare Ctr
ATTN: AMSEL-SW-OS
Vint Hill Farms Station
001 Warrenton, VA 22186-5100

Dir, Night Vision & Electro-Optics Ctr
CECOM
ATTN: AMSEL-NV-D
001 Fort Belvoir, VA 22060-5677

Cdr, Atmospheric Sciences Lab
LABCOM
ATTN: SLCAS-SY-S
001 White Sands Missile Range, NM 88002

Cdr, Harry Diamond Laboratories
ATTN: SLCHD-CO, TD (In turn)
2800 Powder Mill Road
001 Adelphi, MD 20783-1145